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Characterization of optical turbulence (C_n^2) data measured at the ARL A_LOT facility

by Arnold Tunick, Nikolay Tikhonov, Mikhail Vorontsov, and Gary Carhart

ARL-MR-625

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Army Research Laboratory
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14. ABSTRACT The Army Research Laboratory (ARL), Atmospheric Laser Optics Testbed (A_LOT) is a unique experimental facility with which to measure optical turbulence (C_n^2) intensity and investigate its effects on infrared imaging and laser optics communications. Within the A_LOT, an atmospheric boundary layer scintillometer records C_n^2 data over a near horizontal, 2.3 km path. The optical path extends from the top of a tall water tower to the Intelligent Optics Laboratory (IOL) rooftop at ARL. The mid-point elevation of the optical path is approximately 40 m above ground level. In this paper, we present an overview of selected optical turbulence and meteorology data collected at the A_LOT facility and identify several viable research areas that focus on optical turbulence (C_n^2) measurement, modeling, and analysis.				
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Contents

Figures	iii
1. Introduction	1
2. Selected optical turbulence and local meteorology data	4
3. Topographic and meteorological influences	15
3.1 Altitude dependence	15
3.2 Energy budgets	16
3.3 Microclimate around buildings and forests	18
4. Summary and conclusions	19
Acknowledgment	20
Literature cited	21
Distribution	24

Figures

Figure 1. Time series of optical turbulence (scintillometer) data collected at 2 m (a.g.l.) over a 450 m path under typical daytime, clear-sky, unstable atmospheric conditions [12].	2
Figure 2. Time series of optical turbulence (scintillometer) data collected over a 2.3 km elevated path. The turbulence intensity is quite low for both daytime and nighttime.	2
Figure 3. A schematic of the ARL A_LOT optical path.....	3
Figure 4. An aerial photo of the A_LOT propagation path (data from terrafly.com).....	3
Figure 5. Time series of optical turbulence (scintillometer) data collected over a 2.3 km elevated path on 02 December 2004.....	6
Figure 6. Time series of local meteorological data collected at ~ 2 m above the IOL rooftop on 02 December 2004.	6
Figure 7. Same as FIG. 5 except on 12 December 2004.....	7

Figure 8. Same as FIG. 6 except on 12 December 2004.....	7
Figure 9. Same as FIG. 5 except on 25 January 2005.....	8
Figure 10. Same as FIG. 6 except on 25 January 2005.....	8
Figure 11. Same as FIG. 5 except on 25 March 2005.....	9
Figure 12. Same as FIG. 6 except on 25 March 2005.....	9
Figure 13. Same as FIG. 5 except on 25 April 2005.	10
Figure 14. Same as FIG. 6 except on 25 April 2005.	10
Figure 15. Same as FIG. 5 except on 01 May 2005.....	11
Figure 16. Same as FIG. 6 except on 01 May 2005.....	12
Figure 17. Same as FIG. 5 except on 12 June 2005.....	13
Figure 18. Same as FIG. 6 except on 12 June 2005.....	13
Figure 19. Same as FIG. 5 except on 19 June 2005.....	14
Figure 20. Same as FIG. 6 except on 19 June 2005.....	14
Figure 21. Optical turbulence (scintillometer) data collected over a 400 m elevated path in the Netherlands on 15 February 2002 [26]. Note the high values of $Cn2$ at night.	16
Figure 22. One-dimensional (energy budget model) calculation of path-averaged $Cn2$ compared to measured A_LOT scintillometer data on 17 December 2002.	17
Figure 23. Finite-difference model results for wind flow around multiple buildings [34].	18
Table 1. Characterization of selected optical turbulence and local meteorology data.	5

1. Introduction

Optical turbulence is an atmospheric effect that acts on the propagation of light waves. It is brought about by fluctuations in the refractive index in air, i.e., air density, which affects the speed at which light wave fronts propagate. Atmospheric refractions of electromagnetic energy can cause spatial and temporal (intensity) variations in transmitted signals [1-4]. In turn, these effects can significantly degrade (blur, shimmer, and distort) infrared images or increase transmission bit error rates in free-space laser and ground-to-satellite communication systems. Hence, there is a growing need for increasingly accurate and reliable optical turbulence information.

As an example, optical turbulence was studied intently during an experiment to establish the first known optical communication link using lasers (from a mountaintop observatory) to a low earth orbiting satellite [5]. The number of arc-seconds of beam wander due to boundary layer turbulence that affected the performance of their ground-to-satellite optical uplink was found to be (on average) 1.5 to 5.0. This affected light deviations at their receiver in space of approximately 2.2 to 7.3 m. Wilson et al. commented, “If left uncompensated (i.e., no adaptive beam steering techniques applied) these effects would cause fades and surges in the uplink signal, and result in high bit errors in the uplink communications data stream.”

A quantitative measure of the intensity of optical turbulence is the refractive index structure parameter, C_n^2 , where averaged C_n^2 is often determined as a function of local differences in temperature, moisture, and wind velocity at discrete points [6-8]. Hill [9] describes a useful expression for C_n^2 in the form,

$$C_n^2 = \overline{[n(x) - n(x+r)]^2} r^{-2/3}, \quad (1)$$

where n is the index of refraction in air, x is position, and $|r|$ is an eddy length scale between the inner (dissipation) and outer (energy producing) turbulent scales [7, 10]. In this form, we see that C_n^2 is a parameter related to the refractive index variance over the small increment of distance $|r|$.

In the atmospheric surface layer, we generally observe values of C_n^2 to range from about 10^{-12} to $10^{-16} \text{ m}^{-2/3}$ [11]. High values of C_n^2 , $10^{-13} \text{ m}^{-2/3}$ or greater usually indicate a highly turbulent atmosphere and the potential for considerable visual blurring, e.g., the wavy lines and visual blurring one might encounter looking out over a hot paved road. We often experience this degree of turbulence close to the ground on clear days, under unstable (surface-heated, convective) conditions (Fig. 1). In contrast, typical daytime high values of C_n^2 over oceans may be about $10^{-14} \text{ m}^{-2/3}$. Alternately, lower values of C_n^2 , 10^{-16} to $10^{-15} \text{ m}^{-2/3}$, indicate more adiabatic conditions (i.e., near-neutral

atmospheric stability), like that which occurs on windy or cloudy days (and nights) or during the transitional periods after sunrise or before sunset (Fig. 2). One might consider such atmospheric optical turbulence negligible over shorter (≤ 2 km) optical paths although there could be other image-degrading effects due to aerosols, precipitation, fog, or smoke.

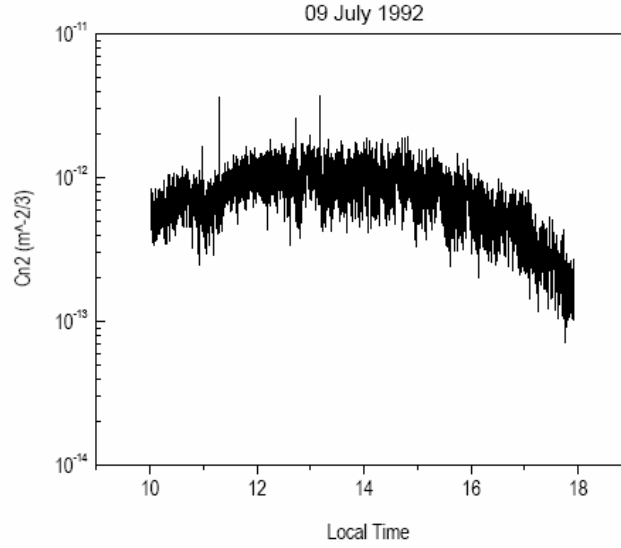


Figure 1. Time series of optical turbulence (scintillometer) data collected at 2 m (a.g.l.) over a 450 m path under typical daytime, clear-sky, unstable atmospheric conditions [12].

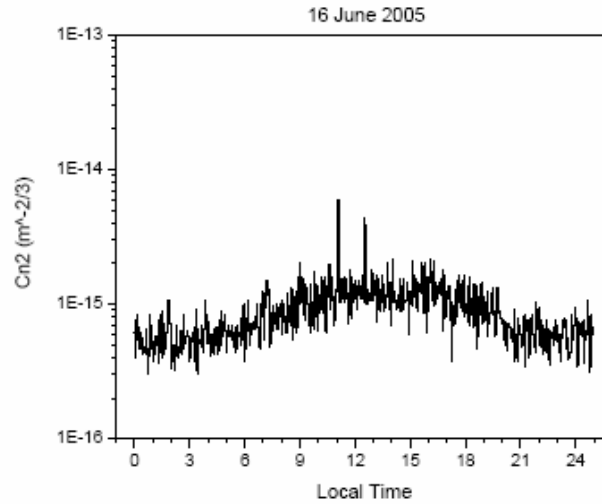


Figure 2. Time series of optical turbulence (scintillometer) data collected over a 2.3 km elevated path. The turbulence intensity is quite low for both daytime and nighttime.

The following paper focuses on optical turbulence (scintillometer) data collected from December 2004 through June 2005 at the Army Research Laboratory (ARL), Atmospheric Laser Optics Testbed (A_LOT) Facility [13]. The scintillometer at A_LOT (i.e., Scintec¹ BLS900) is a remote-sensing instrument that measures optical turbulence intensity ($Cn2$) along a line-of-sight path established between a transmitter and a downrange receiver. Scintillometers operate based on the principle that scintillations or light intensity variations occur as atmospheric density discontinuities create refraction effects in light propagating along a path [14]. The parameter $Cn2$ relates to the intensity of these refraction effects. The average (mid-point) elevation for the scintillometer at A_LOT is approximately 40 m above ground level (a.g.l.). The optical path traverses somewhat complex topography and energy budgets (e.g., an open sand lot, forests, local roads, and buildings) from the top of a tall water tower to the Intelligent Optics Laboratory (IOL) rooftop at ARL (Figs. 3 and 4). About half of the optical path is located over a relatively closed and uniform forest stand (Fig. 4). Naturally, varying wind flow patterns and microclimate along the optical path will affect the A_LOT measured data. We hope to develop and test several new algorithms to represent these processes in future works.

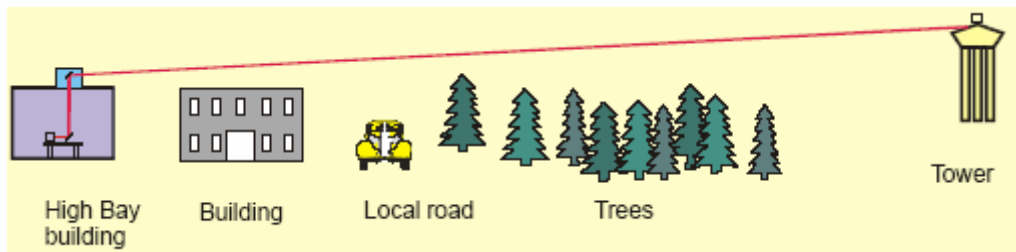


Figure 3. A schematic of the ARL A_LOT optical path.



Figure 4. An aerial photo of the A_LOT propagation path (data from terrafly.com).

¹ The use of commercial or company names with regard to electronic products does not constitute an endorsement by the U.S. Army.

Finally, a Davis Instruments¹ Vantage Pro™ Weather Station collects local meteorology data on a tripod at ~ 2 m above the IOL rooftop. Measured meteorological data include mean temperature, wind speed (small 3-cup anemometer), barometric pressure, relative humidity, and rainfall amount. Later on, we expect to integrate a single 3-axis ultrasonic anemometer (R. M. Young¹ model 81000) along side the rooftop weather station. We expect the ultrasonic micrometeorological sensor to provide quite a lot of useful data for optical turbulence characterization and modeling research, e.g., mean wind velocities and wind flow statistics, mean and fluctuating temperatures, and eddy correlation-derived heat flux and friction velocity.

In Section 2, we present various examples of turbulence and local meteorology data collected at the ARL A_LOT facility. Section 3 discusses possible topographic and meteorological influences on the A_LOT measured turbulence data. In Section 4, we give a summary and identify several viable research areas (projects) that focus on optical turbulence ($Cn2$) measurement, modeling, and analysis.

2. Selected optical turbulence and local meteorology data

Table 1 summarizes the general features of the optical turbulence ($Cn2$) and local meteorology data selected for eight case studies. We chose the dates (from winter to summer) somewhat randomly. The information in Table 1 indicates that the values of $Cn2$ measured over the A_LOT elevated path range from about 2.0×10^{-16} to $4.5 \times 10^{-14} \text{ m}^{-2/3}$ for different meteorological conditions, i.e., for variable wind speeds, relative humidity, and mean temperature. The maximum values for $Cn2$ appear to be about an order of magnitude lower (i.e., less intense) than turbulence data typically measured close to the ground. This may be largely due to altitude dependence of the measured data (see Section 3). Table 1 also provides information regarding the range of wind speeds and the level of humidity (if higher than normal). Yet beyond this, we would like to know what correlations exist between turbulence ($Cn2$) intensity and wind speed. This is a good topic for future investigation. In addition, it would be interesting to explore the relationship between turbulence intensity and cloud cover (and relative humidity).

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Table 1. Characterization of selected optical turbulence and local meteorology data.

Date/Month/Year	Turbulence ($Cn2$)	Meteorology
02 December 2004	8.0×10^{-16} to 4.0×10^{-14}	1.0-2.0 m/s wind speeds
12 December 2004	7.0×10^{-16} to 1.5×10^{-14}	1.0-4.0 m/s wind speeds
25 January 2005	1.0×10^{-15} to 4.5×10^{-14}	1.0-2.5 m/s wind speeds; Calm winds before/after sunrise
25 March 2005	7.5×10^{-15} to 4.0×10^{-14}	1.0-2.5 m/s wind speeds (daytime); Calm winds (nighttime); High relative humidity
25 April 2005	2.0×10^{-15} to 3.0×10^{-14}	1.0-8.0 m/s wind speeds
01 May 2005	3.0×10^{-16} to 4.5×10^{-14}	1.0-8.0 m/s wind speeds; High relative humidity (nighttime)
12 June 2005	2.0×10^{-16} to 3.0×10^{-15}	1.0-4.0 m/s wind speeds (daytime); Calm winds and high relative humidity (nighttime) before sunrise
19 June 2005	1.0×10^{-15} to 4.0×10^{-14}	1.0-6.0 m/s wind speeds

Figure 5 presents the time series of $Cn2$ data collected on 02 December 2004. It is interesting that the turbulence intensities recorded during the nighttime exceed those measured during the daytime. In addition, the $Cn2$ data exhibit a distinct diurnal pattern, wherein local minima in the $Cn2$ data, which occur at or about the sunrise and sunset, border the daytime maximum. This feature is typical of data shown in the literature [12, 15-19]. To some extent, most of the A_LOT $Cn2$ data presented here show one or two local daytime maxima in turbulence intensity (even if no clear local minima at sunrise and sunset are present). Figure 6 presents the temperature, relative humidity, and wind speed data for this case. For reasons unknown, the data record is incomplete. It is interesting, however, that the temperature steadily decreases (and the humidity increases) from ~ 0700 LT until the end of the data record at ~ 1400 LT. These data indicate (possibly) the passage of a cold front. At the same time, Fig. 6 shows that the nighttime winds were sporadic and light (i.e., 1.0 -2.0 m/s)

Figure 7 presents the time series of $Cn2$ data collected on 12 December 2004. Here, the turbulence intensities recorded during the nighttime were (on average) quite low (i.e., $1.5 \times 10^{-15} \text{ m}^{-2/3}$). These low turbulence conditions continued through the morning hours. From about 1000-1400 LT, however, Fig. 7 shows a daytime maximum in $Cn2$ ($\sim 1.0 \times 10^{-14} \text{ m}^{-2/3}$). Figure 8 presents the local meteorology data for this case. The wind speeds were sporadic at about 1.5-2.0 m/s (on average). From about 0900-1400 LT, the data show a slight increase in wind speed. This appears to correspond to increased turbulence ($Cn2$) intensity at that time.

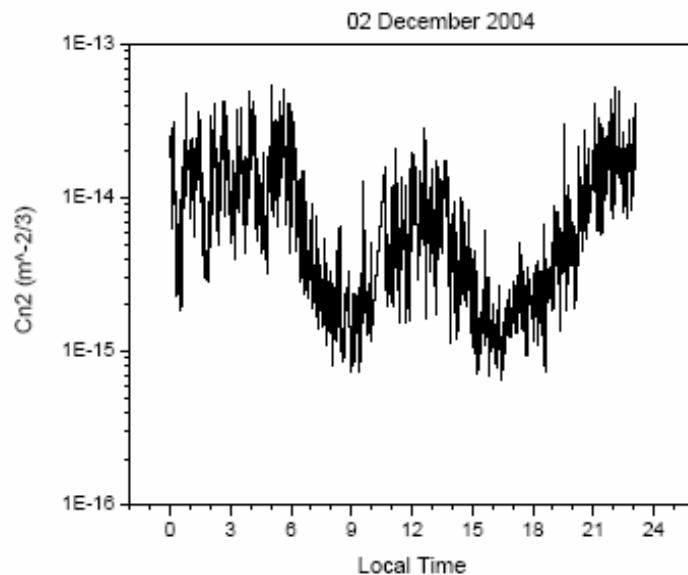


Figure 5. Time series of optical turbulence (scintillometer) data collected over a 2.3 km elevated path on 02 December 2004.

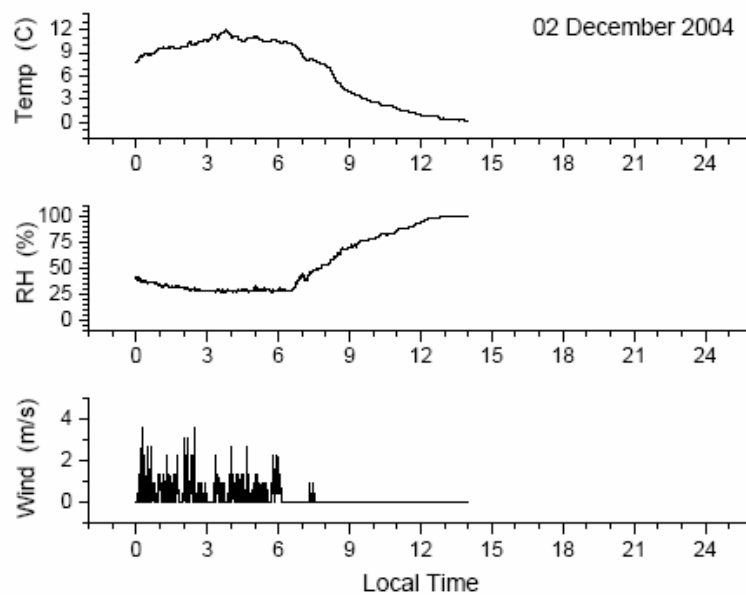


Figure 6. Time series of local meteorological data collected at ~ 2 m above the IOL rooftop on 02 December 2004.

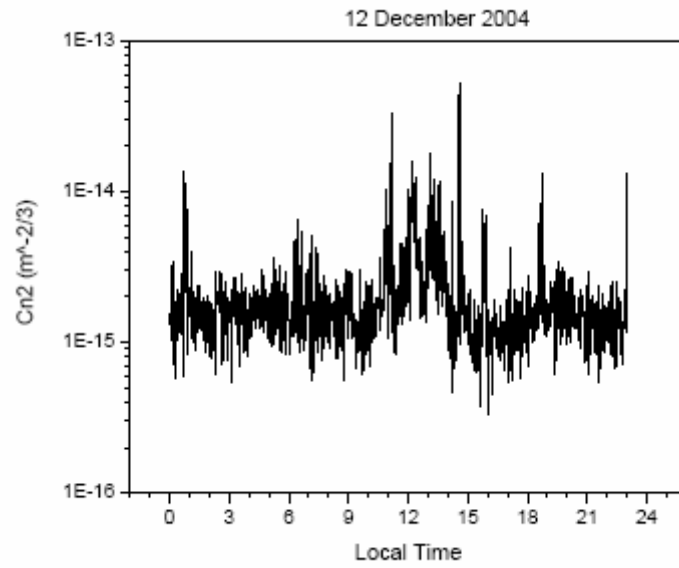


Figure 7. Same as FIG. 5 except on 12 December 2004.

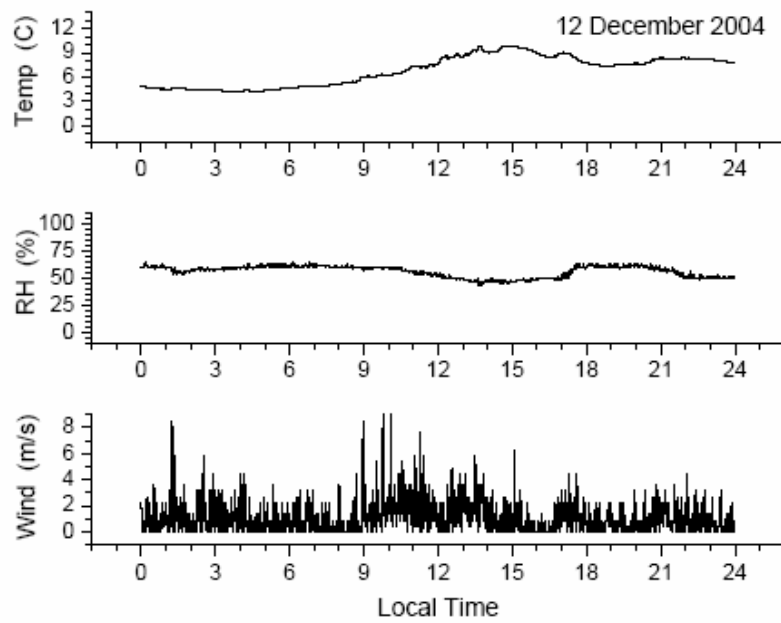


Figure 8. Same as FIG. 6 except on 12 December 2004.

Figure 9 presents the time series of $Cn2$ data collected on 25 January 2005. At first glance, the data record is quite noisy. If we consider only the mean, however, a somewhat normal diurnal pattern is discernable. The range of turbulence intensity (overall) for this case is very high ($\sim 6.0 \times 10^{-15}$ to $3.0 \times 10^{-14} \text{ m}^{-2/3}$). Figure 10 presents the temperature, relative humidity, and wind speed data for 25 January 2005. Here again, the wind speeds (daytime and nighttime) were sporadic at about 1.0-2.5 m/s (on average). However, the data in Fig. 10 shows two periods of calm winds.

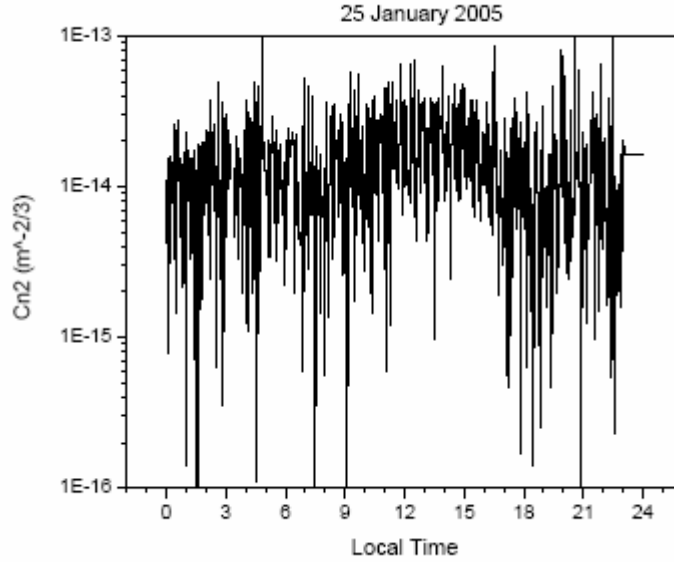


Figure 9. Same as FIG. 5 except on 25 January 2005.

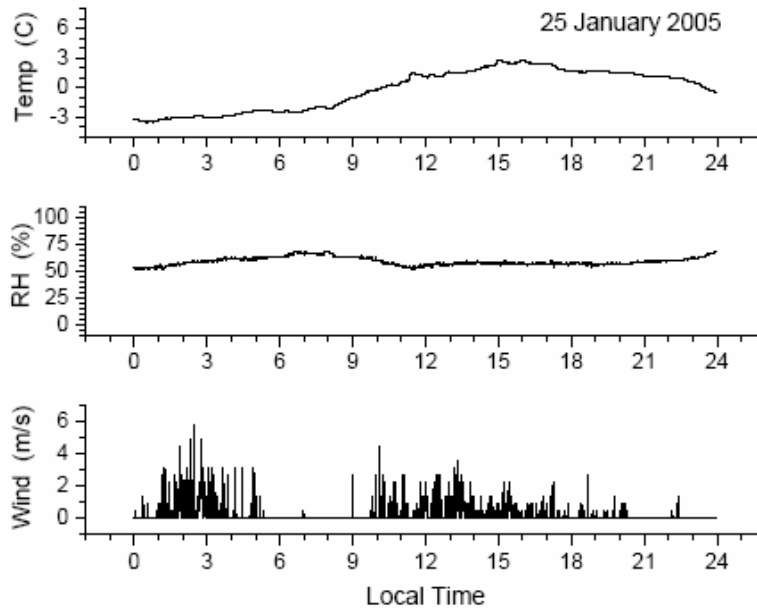


Figure 10. Same as FIG. 6 except on 25 January 2005.

Figure 11 presents the time series of $Cn2$ data collected on 25 March 2005. It is interesting that these $Cn2$ data show very little diurnal variability. In addition, the average turbulence intensity for this case is quite high ($\sim 2.0 \times 10^{-14} \text{ m}^{-2/3}$). Figure 12 presents the local meteorology data for this case. The daytime wind speeds were (on average) 1.0-2.0 m/s with mostly calm winds at night.

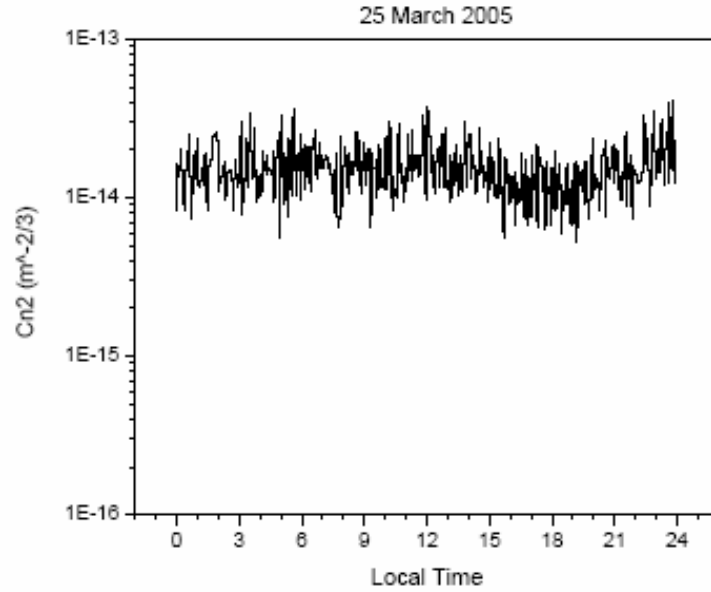


Figure 11. Same as FIG. 5 except on 25 March 2005.

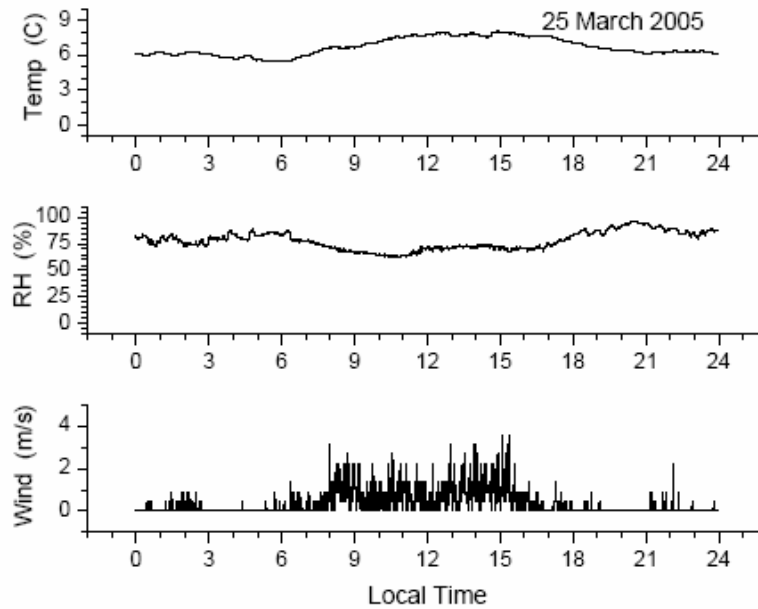


Figure 12. Same as FIG. 6 except on 25 March 2005.

Figure 13 presents the time series of $Cn2$ data collected on 25 April 2005. A few local minima and maxima are discernable. The range of turbulence intensity for this case is comparatively high ($\sim 2.0 \times 10^{-15}$ to $3.0 \times 10^{-14} \text{ m}^{-2/3}$). Figure 14 presents the temperature, relative humidity, and wind speed data for 25 April 2005. For reasons unknown, the data record is incomplete. It is interesting, however, that the temperature steadily decreases (and the relative humidity increases) from 0800 LT until the end of the data record at 1200 LT. Like the data shown in Fig. 6, this record also suggests a change in air mass (i.e., a cold front). In contrast, though, the data in Fig. 14 show that the nighttime wind speeds were stronger (i.e., 3.0 -5.0 m/s).

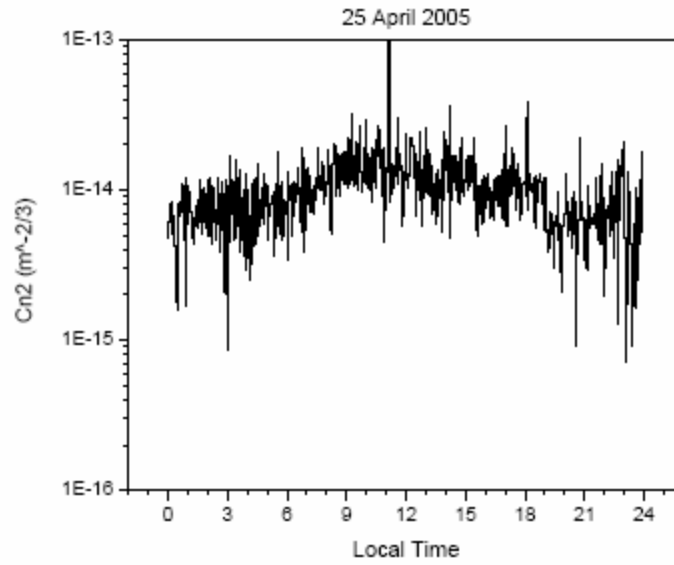


Figure 13. Same as FIG. 5 except on 25 April 2005.

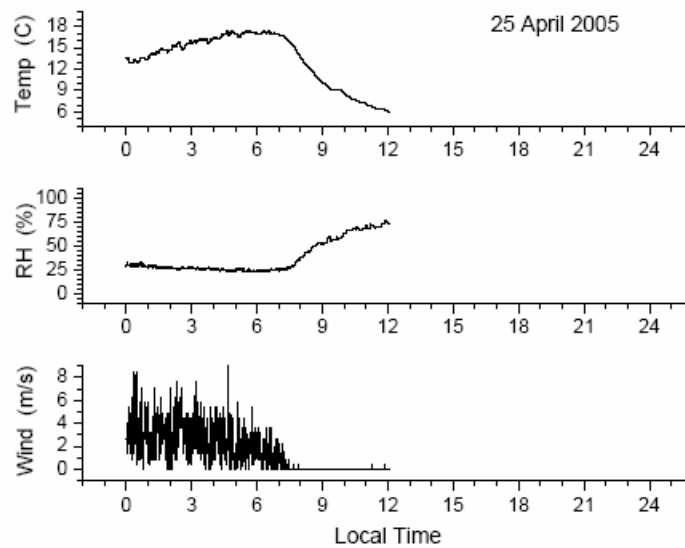


Figure 14. Same as FIG. 6 except on 25 April 2005.

Figure 15 presents the time series of $Cn2$ data collected on 01 May 2005. These data show a few short intervals of high turbulence intensity ($\sim 3.0\text{-}4.0 \times 10^{-14} \text{ m}^{-2/3}$) at about 1000 and 2230 LT. The data also show a brief period of very low $Cn2$ ($\sim 4.0 \times 10^{-16} \text{ m}^{-2/3}$) occurring just after 0300 LT. Additionally, a two other minima (at about 0730 and 1930 LT) are apparent. The average daytime turbulence intensity is about $1.0 \times 10^{-14} \text{ m}^{-2/3}$. Figure 16 presents the local meteorology data for this case. On average, the nighttime and daytime wind speeds were moderate (and sporadic), i.e., 2.0-6.0 m/s. Interestingly, Fig. 16 shows that (in the morning) there was an increase in wind speed, which appears to correspond to an increase in turbulence ($Cn2$) intensity at that time. However, a period of high turbulence also occurs late at night when relatively calm winds ($\leq 1.0 \text{ m/s}$) are present. As mentioned above, this is an interesting topic for future research.

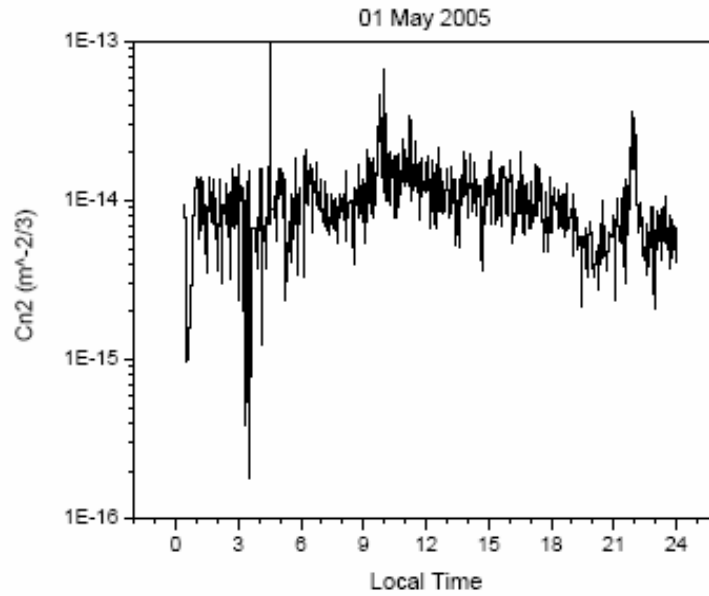


Figure 15. Same as FIG. 5 except on 01 May 2005.

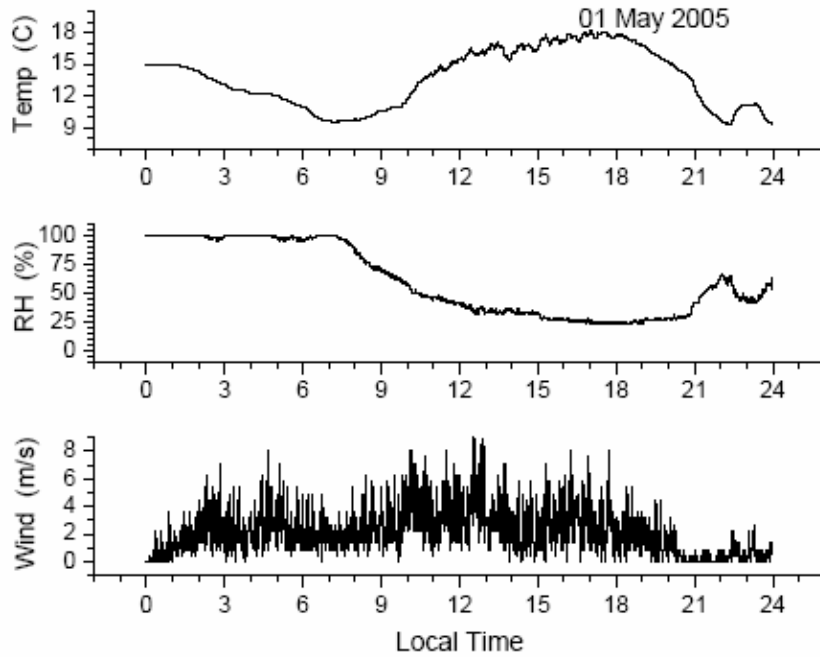


Figure 16. Same as FIG. 6 except on 01 May 2005.

Figure 17 presents the time series of *Cn2* data collected on 12 June 2005. These *Cn2* data show a clear daytime local maximum and two nighttime local minima. In addition, the average turbulence intensity for this case is quite low ($\leq 1.5 \times 10^{-15} \text{ m}^{-2/3}$). Figure 18 presents the temperature, relative humidity, and wind speed data for this case. The nighttime relative humidity is very high and the wind speeds are calm before sunrise. After sunrise, the daytime wind speeds were about 2.0-4.0 m/s.

Figure 19 presents the time series of *Cn2* data collected on 19 June 2005. Like the data shown in Fig. 5, these *Cn2* data exhibit a distinct diurnal pattern, wherein local minima border the daytime maximum. In contrast, however, the data in Fig. 19 show an additional minimum in *Cn2* occurring at about 1500 LT. Cloud cover may explain this brief period of low turbulence. The meteorology data for this case (Fig. 20) tends to support to the claim, wherein temperatures decrease slightly (e.g., possibly due to clouds) from 1430-1600 LT. Shortly afterward, the wind speeds increase from 2.0 to 4.0 m/s with wind gusts up to 6.0 m/s.

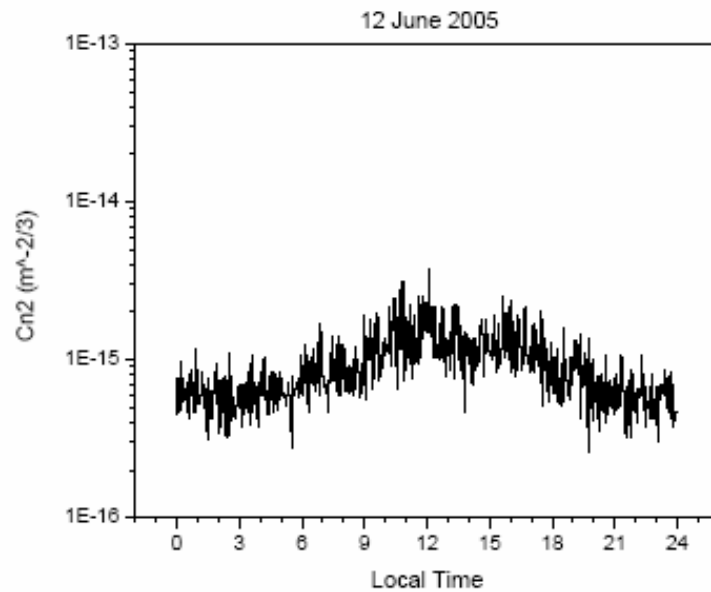


Figure 17. Same as FIG. 5 except on 12 June 2005.

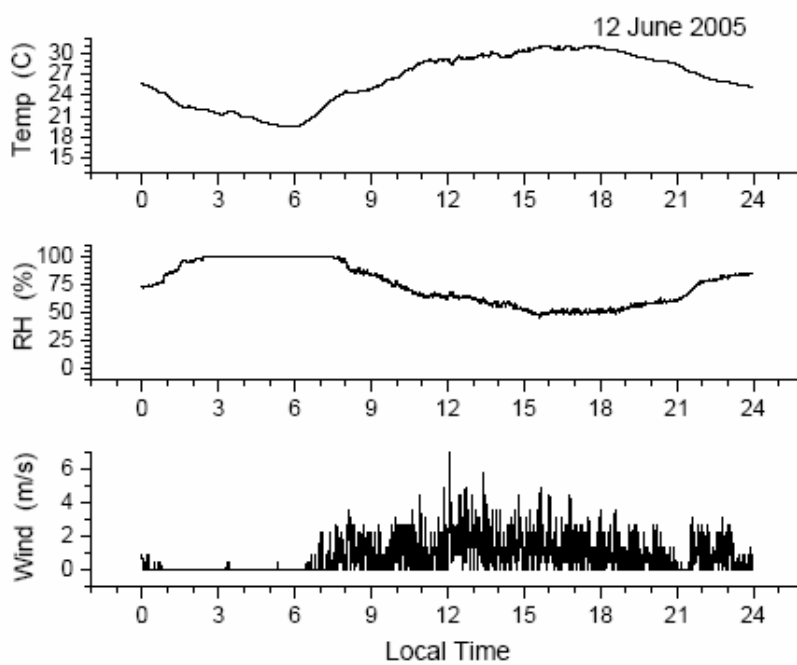


Figure 18. Same as FIG. 6 except on 12 June 2005.

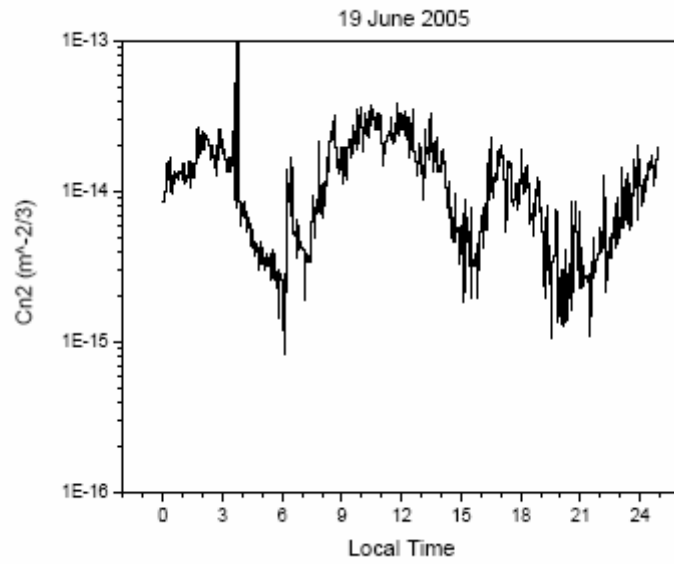


Figure 19. Same as FIG. 5 except on 19 June 2005.

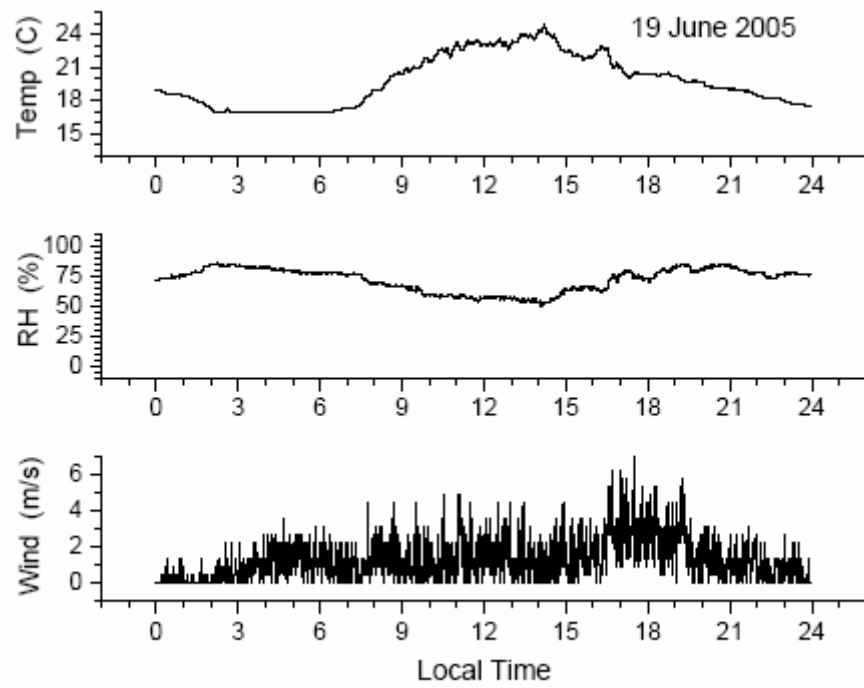


Figure 20. Same as FIG. 6 except on 19 June 2005.

3. Topographic and meteorological influences

The average height of the A_LOT optical path that extends from the water tower to the IOL rooftop is about 40 m above ground level (a.g.l.). Certainly, changing topography and non-uniform meteorology conditions may influence the measured data. In this section, we briefly discuss some possible effects.

3.1 Altitude dependence

Tatarski [7] suggested the following power-law exponent model to extrapolate vertical profile information from discrete estimates of Cn^2 close to the ground, i.e.,

$$C_n^2(z) = C_{n\ ref}^2 \cdot \left(\frac{z}{z_{ref}} \right)^{-x}, \quad (2)$$

where the power-law exponent is $x = 4/3$ for unstable atmospheric conditions and $x = 2/3$ for stable or adiabatic (i.e., near-neutral) conditions. For the A_LOT optical path, this corresponds to possible vertical scaling of 1.84% and 13.6% respectively, in comparison to data measured at 2 m (a.g.l.). Wyngaard et al. [20] and others [21-24] investigated Tatarski's power-law model using data collected during several outdoor field trials. Ben-Yosef et al. [22] for example, found Eq. (2) to be in good agreement ($\sim 84\%$ correlation, on average) with observed data for the range $10 < z \leq 100$ m, particularly for the convective (daytime) case.

The literature shows additional Cn^2 data collected along elevated paths [25-27]. Kohsiek [26], for example, presents Cn^2 data collected during the winter at about 42 m (a.g.l.), which range from about $1.0\text{--}8.0 \times 10^{-15} \text{ m}^{-2/3}$ (Fig. 21). These data also suggest that the values for Cn^2 may be about an order of magnitude lower than turbulence data measured close to the ground. Furthermore, it is interesting to note in Fig. 21 that the turbulence intensities recorded during the nighttime exceed those measured during the daytime (e.g., this is similar to the A_LOT data shown in Fig. 5). Finally, a diurnal pattern is discernable in Fig. 21, wherein local minima border the daytime maximum, albeit the level of daytime turbulence here is quite low.

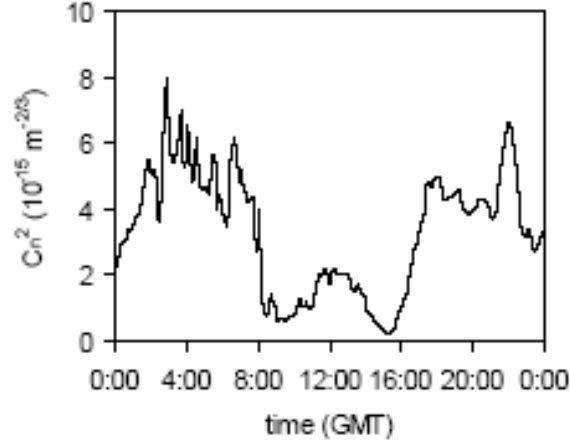


Figure 21. Optical turbulence (scintillometer) data collected over a 400 m elevated path in the Netherlands on 15 February 2002 [26]. Note the high values of Cn^2 at night.

3.2 Energy budgets

One-dimensional (1-D) computer models for path-averaged Cn^2 have been developed via energy budget considerations, e.g., from computed net radiation, effective surface temperature, soil, sensible, and latent (moisture) heat fluxes [19, 28-30]. While calculations of this kind have been quite useful for uniform meteorology and turbulence conditions, we recognize that formulating improved models, which are at least two-dimensional, will be advantageous to determine optical turbulence (Cn^2) in small finite increments along more complicated lines-of-site.

In any case, Fig. 22 shows an example 1-D (energy budget model) calculation of path-averaged Cn^2 compared to measured A_LOT scintillometer data. Overall, the agreement is satisfactory. However, several underlying assumptions are associated with the model output. For example, we assume the surface roughness length is large (e.g., $z_0 = 1.4$ m) and the wind speeds are not less than 4.0 m/s (daytime and nighttime). These assumptions are made because of several known difficulties in the application of traditional similarity theory [30] for calculating turbulence structure from micro-meteorological data, especially for the stable case and as local ΔT temperature differences become small [18, 31, 32]. As an example, Tunick [31] found that the roughness height and reference level wind speeds at night need to be large enough to affect values for the similarity scaling length of $L = 13$ m or more, otherwise, the model breaks down and the computation is not viable.

A curious result in Fig. 22 relates to the prediction of ‘low’ turbulence after sunrise and before sunset. The energy budget model computes the daily minima in $Cn2$ about 1.0 hour later than the scintillometer data in the morning and about 1.0 hour earlier in the afternoon. In general, local minima in $Cn2$ occur as ΔT temperature (and humidity) differences become small. Here, the scintillometer data and model appear to disagree when (i.e., at what time) surface heating overturns the nighttime stable inversion (and vice versa). In any case, we would encourage further discussion on this point to obtain a better understanding of the problem.

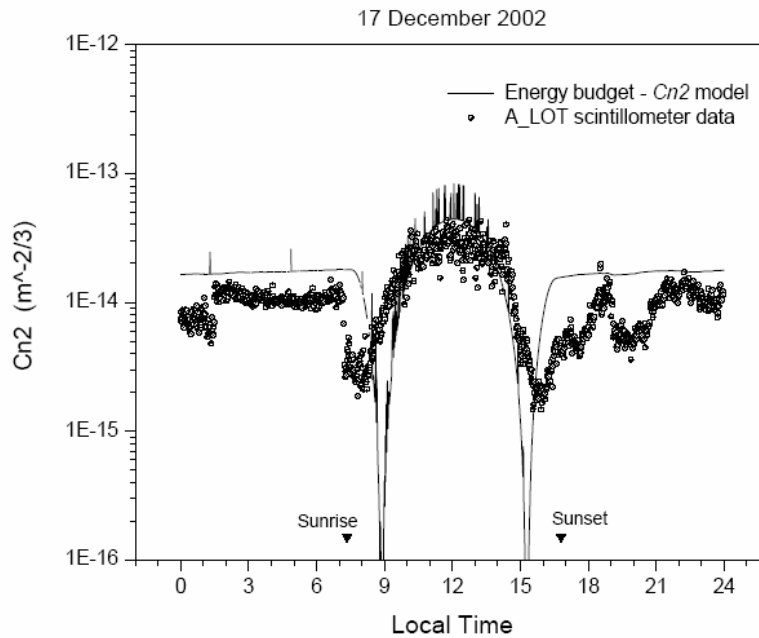


Figure 22. One-dimensional (energy budget model) calculation of path-averaged $Cn2$ compared to measured A_LOT scintillometer data on 17 December 2002.

3.3 Microclimate around buildings and forests

Irregular wind flow patterns around the IOL and the water tower and the effects from wind shears and temperatures across the top of nearby forest canopies may also affect the A_{LOT} measured data. To this end, computer models, like the program code reported in reference [33], may provide some meaningful results (even though pertinent canopy characterization and meteorological data along the optical path are not yet known or available). Additionally, we can begin to formulate basic finite difference models with which to conduct numerical experiments to derive surface layer, wind flow patterns around single and multiple buildings. Here, different building geometries embedded in the model grid (as well a representation of canopy drag forces) will affect the resultant vector wind fields. Figure 23 shows an example model result for a five building array [34]. In the future, we can extend model results of this kind to three-dimensions. Later on, we can include mechanisms (possibly) to account for heating, cooling, and moisture. Our main concern, however, is to maintain computationally efficient program codes that are also flexible with regard to modifications and debugging (thereby allowing application to different kinds of tests).

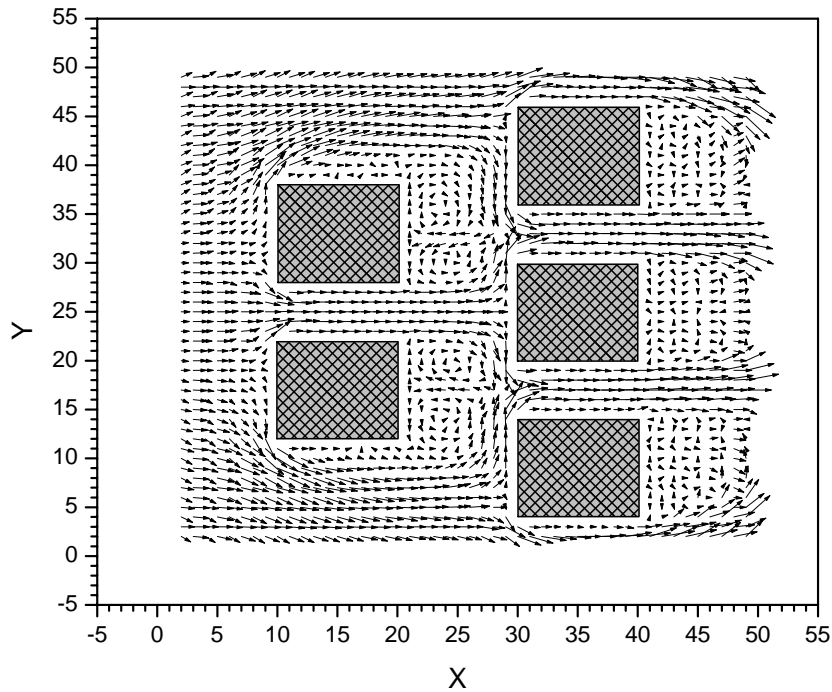


Figure 23. Finite-difference model results for wind flow around multiple buildings [34].

4. Summary and conclusions

In this paper, we presented an overview of selected optical turbulence and meteorology data collected at the A_LOT facility at ARL. We focused on the scintillometer ($Cn2$) data recorded at the IOL from December 2004 through June 2005. We discussed eight case studies with regard to variations in daytime and nighttime turbulence intensity, wind speed, temperature, and relative humidity. At the same time, we discussed some possible topographic and meteorological influences on the measured data and illustrated a few numerical model results aimed to predict these effects.

In addition, we began to identify several viable research areas related to optical turbulence ($Cn2$) measurement, modeling, and analysis. They are as follows:

- Collect data to determine the kinds of correlations that exists between turbulence intensity and crosswind velocity.
- Explore the relationship between turbulence intensity and cloud cover (and relative humidity).
- Analyze and interpret ultrasonic micrometeorological sensor data for use in optical turbulence ($Cn2$) characterization and modeling research.
- Investigate altitude dependence and computer model approximations of $Cn2$.
- Examine diurnal patterns, e.g., local minima and maxima, in recorded $Cn2$ data and in numerical model predictions.
- Conduct statistical analyses of selected $Cn2$ data (e.g., for different seasons) to determine such quantities as monthly mean (daytime and nighttime).
- Investigate models, which are at least two-dimensional, to determine optical turbulence ($Cn2$) in small finite increments along more complicated lines-of-site, e.g., across non-uniform energy budgets.
- Investigate algorithms to represent wind flow patters and microclimate around complex structures (e.g., forests, buildings, etc.) to determine their effects on $Cn2$ and electro-optical propagation.

Current Army transformation programs are developing and integrating laser optics communication systems and sensors as a viable means to transmit large amounts of data, with limited interference, and at high data rates. We anticipate that the research areas identified here will provide much useful information related to performance assessment and analysis of new Army systems.

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